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The GRB-Supernova Connection

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9.1 Introduction

The discovery and localisation of the first afterglows of GRBs rapidly led to the establishment of the long-sought distance scale for the sources (see Chapter 4), which began an earnest observational hunt for the progenitors. A preponderance of evidence linked long-duration, soft-spectrum GRBs with the death of massive stars. The observations of the GRB–supernova (SN) connection, the main subject of this chapter, present the most direct evidence of this physical link.

Well before the Afterglow Era, Paczyński (1986) noted that "cosmological" distances of GRBs would imply that the energy release in γ rays would be comparable to the energy release in a typical SN explosion. Seen as more than just a coincidence, this energetics connection between GRBs and the death of massive stars was fleshed out† into what is now referred to as the *collapsar model* (Woosley 1993, 1996, MacFadyen & Woosley 1999). Briefly, the collapsar involves the core-collapse explosion of a stripped-envelope massive star. Matter flows towards a newly formed black hole or rapidly spinning, highly magnetized neutron star ("magnetar"; e.g., Bucciantini et al. 2009). Powerful jets plow through the collapsing star along the spin-axis, eventually obtain relativistic speeds, and produce GRBs. Enough ^{56}Ni is produced near the central compact source to power a supernova explosion of the star. The original "failed Ib" model posited that little ^{56}Ni would be produced during core-collapse of a massive star that produces a GRB, and thus no traditional

† The possible connection between GRBs and SNe was actually first studied observationally in the original GRB discovery paper of Klebesadel et al. (1973), following the suggestion that γ rays could be produced in SN shock breakout (Colgate 1968).

SN would be visible. Chapter 10 is an in-depth review of core-collapse progenitor models, including collapsar and millisecond-magnetar-driven models.

After the first few afterglow localizations of (long-duration; Kouveliotou et al. 1993) GRBs, a qualitative connection of the events with star-formation regions and star-forming galaxies began to emerge (e.g., Paczyński 1998). The close proximity of GRBs to star formation, surprising to many, was not a natural expectation of degenerate merger models (e.g., Fryer et al. 1999; Bloom et al. 1999b). Instead, this evidence directly implicated models where the progenitor does not move far from its birthsite and produces a GRB on timescales smaller than the typical duration of star-formation episodes. The discovery of the energetic core-collapse supernova 1998bw associated with the very underluminous GRB 980425 (see section 9.2.1) provided the first concrete evidence for a GRB connection with a massive star death (though the relationship between GRB 980425, at the low redshift of $z = 0.0085$, and "cosmological" GRBs would be debated for years). As statistical statements about the physical connection of cosmological GRBs with ongoing star formation amassed (Bloom et al. 2002a, Le Floc'h et al. 2003, Christensen et al. 2004, Fruchter et al. 2006), individual events began to exhibit credible *photometric* evidence for a SN explosion contemporaneous with the GRB (Bloom et al. 1999a, Galama et al. 2000, Bloom et al. 2002b, Garnavich et al. 2003, Zeh et al. 2004). The definitive evidence for the GRB-SN connection was finally established by a few events which, through *spectroscopic* identification of SN features well after the GRB event (see section 9.2), clinched the physical association. An early review of the GRB-SN connection was given in van Paradijs (1999) and more recent dedicated reviews were given in Soderberg (2006), Woosley & Bloom (2006) and Della Valle (2007).

We begin this chapter by reviewing the strongest current observational evidence for the GRB-SN connection; Chapter 10 provides an overview of how these observations tie, theoretically, some GRBs to the death of massive stars. We summarize 30 GRB-SN associations and focus on five ironclad GRB-SN associations (GRB 980425/SN 1998bw, GRB 030329/SN 2003dh, GRB 031203/SN 2003lw, GRB 060218/SN 2006aj, GRB 100316D/SN 2010bh), discovered by four different satellites, which, in concert, constitute irrefutable spectroscopic evidence for the association of GRBs and SNe. We highlight the subsequent insight into the progenitors enabled by detailed observations. We next present some of the supporting evidence for the GRB-SN connection and address the SN association (or lack thereof) with several sub-classes of GRBs, finding that the X-ray Flash (XRF) population is likely associated with massive stellar death whereas short-duration events likely arise from

an older population not readily capable of producing a SN concurrent with a GRB. Interestingly, a minority population of seemingly long-duration, soft-spectrum GRBs show no evidence for SN-like activity; this may be a natural consequence of the range of ^{56}Ni production expected in stellar deaths. We conclude the chapter by providing an outlook for the next decade of GRB-SN research.

9.2 Spectroscopic evidence for GRBs and SNe

9.2.1 GRB 980425/SN 1998bw

GRB 980425 was discovered early in the afterglow era; at the time it exploded only six GRBs had been localized by *BeppoSAX* and only two had measured redshifts, namely GRB 970508 at $z = 0.83$ (Metzger et al. 1997) and GRB 971214 at $z = 3.42$ (Odewahn et al. 1998). In the error circle of GRB 980425, two X-ray sources were found, though the precise characterisation of their respective variability was uncertain. Therefore, the identification of the true X-ray counterpart to GRB 980425 was controversial (Pian et al. 2000, Kouveliotou et al. 2004); as a result, the discovery of a supernova, SN 1998bw (Fig. 9.1), coincident with one of the X-ray sources was not immediately taken as unequivocal evidence for a direct link to GRB 980425.

SN 1998bw was a spectacular event. It was a bright ($M_B = -18.7$ mag at peak), broad-lined Type Ic SN (Galama et al. 1998) suggesting a significant amount of mass with very fast (upwards of $30,000$ km s^{-1}) photospheric expansion (Woosley & Bloom 2006 advocate for the designation as Ic-BL, for broad-lined SN without He, H or Si in the spectrum). The light curve is shown in Fig. 9.2 and its spectral evolution (Patat et al. 2001) is shown in Fig. 9.3. The late-time light curve, extending to 500 days after the GRB, exhibited a decline consistent with cobalt decay to iron (McKenzie & Schaefer 1999, Sollerman et al. 2000). At the time, SN 1998bw was also the brightest radio SN known, indicating, as a means to explain the very high apparent brightness temperature, that the SN was accompanied by a shock wave moving at mildly relativistic speeds (Kulkarni et al. 1998; but see also Waxman & Loeb 1999). Iwamoto et al. (1998) suggested that these observations can be reproduced by an extremely energetic explosion of a massive star composed mainly of carbon and oxygen (having lost its hydrogen and helium envelopes). Based upon an independent modelling effort, Woosley et al. (1999) concurred with the carbon and oxygen core hypothesis and also argued that SN 1998bw was an asymmetric explosion. Iwamoto et al. (1998) and others at the time used the term "hypernova" (Paczyński 1998) to describe such a very energetic SN, modelled to have released roughly 10

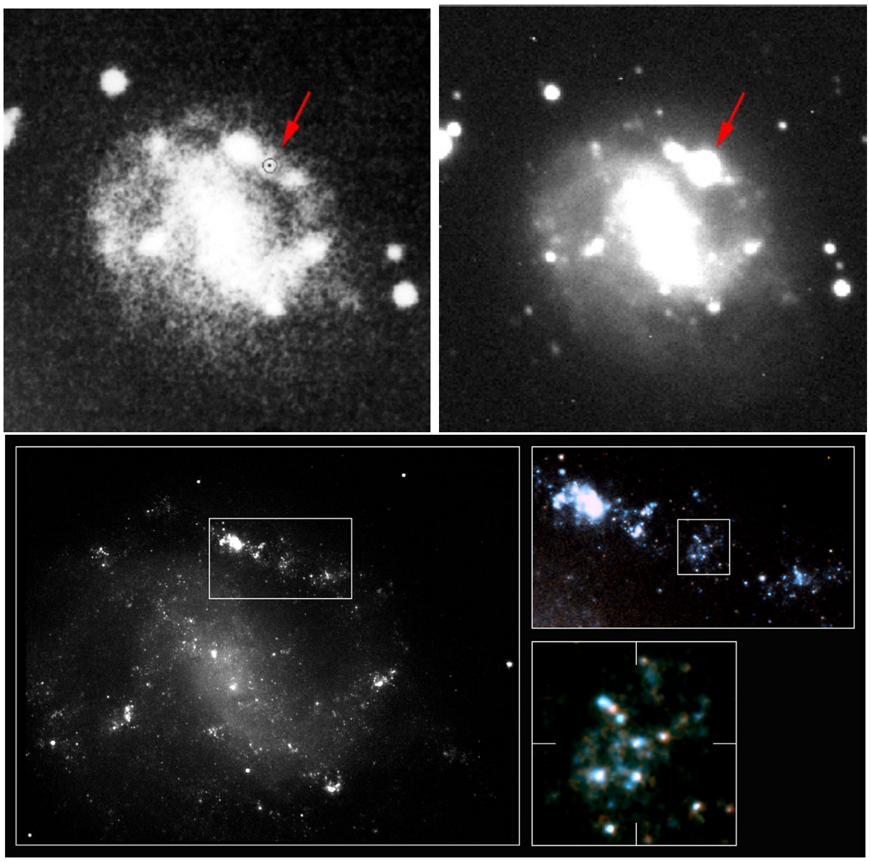

Fig. 9.1. Discovery of SN 1998bw associated with GRB 980425. The upper panels show the images of the host galaxy of GRB 980425, before (left) and shortly after (right) the occurrence of SN 1998bw (Galama et al. 1998). The bottom panel shows a late *HST* image of the host galaxy and SN 1998w. The 3-step zoom-in shows SN 1998bw 778 days after the explosion embedded in a large star-forming region of a spiral arm (Fynbo et al. 2000).

times more energy than in a typical (10^{51} erg) SN. We caution here that the term “hypernova” is a theory-laden classification pertaining to energetics; it is entirely possible to have a core-collapse SN with large expansion velocity ($\gtrsim 20,000$ km s^{-1}) yet typical (10^{51} erg) energy coupled to the ejecta.

No traditional optical afterglow (as seen in most other GRBs; see Chapters 4–6) was detected. Moreover, the comparatively low energy output of GRB 980425 (see e.g., Kaneko et al. 2007) and its low redshift were considered as pointing to a different class of GRB (Kulkarni et al. 1998, Bloom et al. 1998), not necessarily of the same progenitor origin as the truly cosmological GRBs (loosely defined as having a significant redshift, a high energy

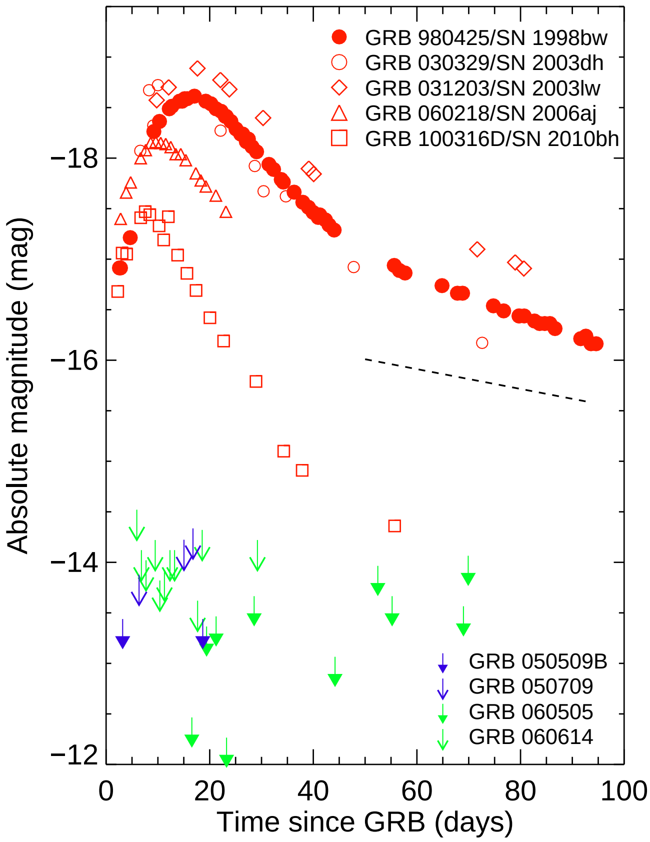

Fig. 9.2. Light curves of spectroscopic GRB-SNe contrasted with upper limits on SNe in SN-less GRBs. The red data points are the light curves of the GRB-SNe 1998bw (Galama et al. 1998), 2003dh (Hjorth et al. 2003), 2003lw (Malesani et al. 2004), 2006ap (Pian et al. 2006) (bolometric magnitudes adapted from Pian et al. 2006 who used a cosmology with $H_0 = 73$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.72$, $\Omega_m = 0.28$), and 2010bh (Bufano et al. 2011). The upper limits are from the short GRBs 050509B (Hjorth et al. 2005a) and 050709 (Hjorth et al. 2005b) (blue arrows) and two SN-less long GRBs (green arrows) (Fynbo et al. 2006). Approximate bolometric magnitudes are based on R and V band upper limits offset relative to the corresponding SN 1998bw V or R band light curves. Time is in the restframe. The ^{56}Co decay slope is shown for reference (dashed curve).

output in γ rays, $E_\gamma \sim 10^{52}$ erg, and an (optical) afterglow decaying as a power law) that had been detected so far.

Doubts therefore remained about the GRB-SN connection, arising from an

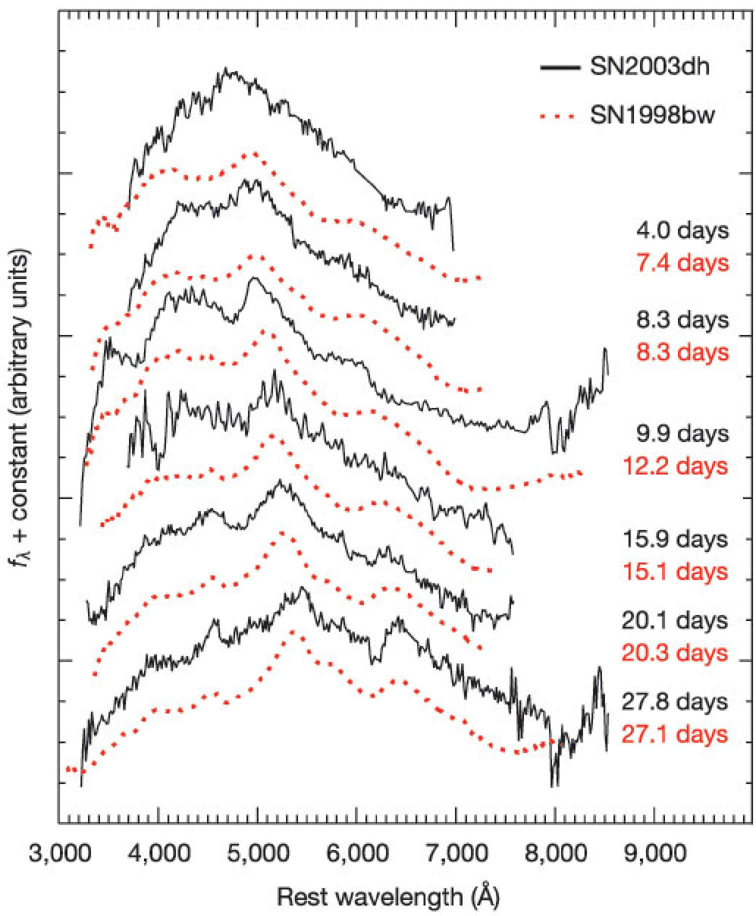

Fig. 9.3. Spectral evolution of GRB-SNe 1998bw (Patat et al. 2001) and 2003dh (Hjorth et al. 2003). Solid lines indicate spectra of SN 2003dh obtained by subtracting a model for the afterglow and host galaxy contributions from the spectra. Dotted red lines indicate spectra of SN 1998bw taken at similar epochs. Times after the GRB are indicated in the rest frame. From Hjorth et al. (2003).

a posteriori statistical argument about the association in time and place with two X-ray sources in the γ-ray error circle, the lack of an optical afterglow, and the low implied energy output; even if the physical connection was believed, GRB 980425 was clearly set apart from the typical cosmological GRBs emitting orders of magnitude more γ-ray energy (Table 9.2).

9.2.2 GRB 030329/SN 2003dh

Though supporting evidence for a GRB-SN connection grew in the interim (see section 9.3), almost 5 years after GRB 980425/SN 1998bw, GRB 030329 eliminated any doubts as to the deep connection of the two phenomena. GRB 030329 was a bright burst detected by the *HETE-2* satellite (Vanderspek et al. 2004, Lipkin et al. 2004). At an inferred redshift of $z = 0.1685$ (Greiner et al. 2003c), it was "truly" cosmological and had a total isotropic energy release 10^4 times that of GRB 980425. Moreover, it was followed by a bright optical afterglow (Price et al. 2003a), helping solidify this event as part of the cosmological GRB class. Several days after the burst, the optical spectrum started to change from a featureless power-law spectrum, characteristic of GRB afterglows, to include more and more SN features (Matheson et al. 2003a, Stanek et al. 2003, Hjorth et al. 2003, Kawabata et al. 2003, Matheson et al. 2003b). By subtracting the afterglow contribution, the SN spectrum could be isolated. It was shown to closely follow that of SN 1998w, thus conclusively showing that the GRB afterglow and SN were spatially coincident and that GRB 030329 and SN 2003dh were co-eval to within a few days (Hjorth et al. 2003) (Fig. 9.3). Lingering possibilities† of a SN preceding the GRB by years to weeks (the so-called "supranova" model; Vietri & Stella 1998) were all but ruled out.

The SN light curve was almost completely masked by the bright afterglow (Lipkin et al. 2004). Only by subtraction of the afterglow was it obvious that SN 2003dh peaked at about the brightness of SN 1998bw but evolved faster (Hjorth et al. 2003, Matheson et al. 2003b) (Fig. 9.2).

In retrospect, the GRB 030329/SN 2003dh connection also eliminated any doubts about the association between GRB 980425 and SN 1998bw. GRB 030329 remains the only GRB with both a clear optical afterglow and a convincing spectroscopically confirmed SN.

9.2.3 GRB 031203/SN 2003lw

GRB 031203 was localized by *Integral* (Sazonov et al. 2004) and the afterglow was subsequently accurately localized by *Chandra* (Gal-Yam et al. 2004), *XMM-Newton* (Vaughan et al. 2004), and the VLA (Gal-Yam et al. 2004) to a galaxy at $z = 0.1055$ (Prochaska et al. 2004). No optical afterglow was detected, but through photometric monitoring of the galaxy a SN light curve bump was detected (Thomsen et al. 2004, Cobb et al. 2004, Gal-Yam et al. 2004).

† Favored by the now questionable identification of spectral lines in X-ray afterglow spectra. See also Chapters 4 and 5.

Spectra of the SN obtained by Malesani et al. (2004) revealed broad-line features similar to those seen in SN 1998bw and SN 2003dh. While the peak brightnesses of SN 1998bw and SN 2003dh were similar, SN 2003lw was brighter by about 0.3–0.5 mag at peak; the uncertainty in the intrinsic brightness reflects a large Galactic extinction towards the field, but SN 2003lw nevertheless provides strong evidence that GRB SNe are not standard candles (see Fig. 9.4).

While the large column density of Galactic dust was a nuisance — dimming and reddening the SN and the afterglow — it allowed for a novel measurement: two radially expanding halos of X-ray emission centered on the GRB were discovered in *XMM-Newton* observations (Vaughan et al. 2004). Because of the time delay due to the longer distance traveled by the light in the rings this allowed a reconstruction of the prompt X-ray flux of GRB 031203 (Watson et al. 2004, Tiengo & Mereghetti 2006, Watson et al. 2006). It was suggested that the fluence in X rays dominates that of the hard-energy emission (though see Prochaska et al. 2004); in other words, had a hard X-ray detector observed the prompt emission of GRB 031203, it might have been classified as an X-ray flash (XRF: a dominant fraction of the total prompt fluence are detected as X rays rather than γ rays; Heise et al. 2001). Therefore, we take SN 2003lw as reasonable spectroscopic evidence for an XRF-SN connection.

While Malesani et al. (2004) reported evidence for a very red, faint infrared afterglow, GRB 031203 was essentially SN dominated. Consequently, Thomsen et al. (2004) speculated that *Swift* would not only be a GRB mission, but also a discoverer of SNe as they explode. This prediction came to fruition with GRB 060218/SN 2006aj.

9.2.4 GRB 060218/SN 2006aj

GRB 060218 was localized by the *Swift* satellite to a galaxy at $z = 0.0335$ (Mirabal et al. 2006). Campana et al. (2006) and Waxman et al. (2007) argued that *Swift* detected emission due to the shock breakout of the associated SN (see, however, Butler 2007 and Ghisellini et al. 2007). SN 2006aj was fainter than the other GRB SNe, providing additional evidence for a substantial dispersion in the peak magnitudes and rise times of GRB SNe (Pian et al. 2006, Modjaz et al. 2006, Sollerman et al. 2006, Ferrero et al. 2006) (Fig. 9.2). Building on the 030723 (Fynbo et al. 2004), 020903 (Soderberg et al. 2005) and 031203 hypothesis of an XRF-SN connection, GRB 060218 was classified as an XRF (though the duration [> 1000 s] of the event was very long compared to other XRFs; Campana et al. 2006).

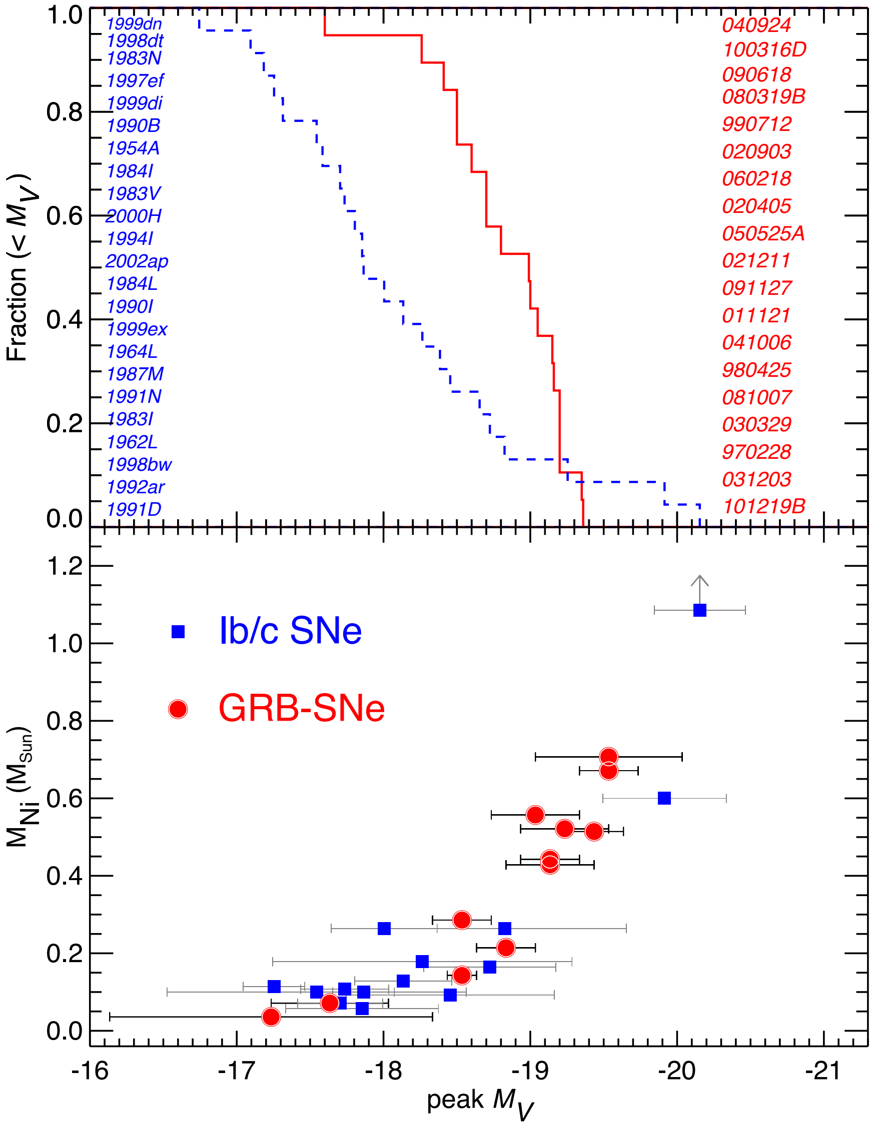

Fig. 9.4. (*Top*) Comparison of the peak brightness of SNe related to GRBs/XRFs (solid cumulative histogram) with local Ibc SNe with well-measured peak brightnesses (dashed histogram); updated from Woosley & Bloom (2006). Historical Type Ib/c SNe are listed on the left. Only those events with a "C" grade or better from Table 9.1 are shown. To mitigate the numerous biases in finding SNe associated with GRB/XRFs, Woosley & Bloom (2006) considered as upper limits the non-detections from the literature and bump claims with less firm SN detections, finding a statistical consistency of peak brightness distributions of the two populations. (*Bottom*) Comparison of implied ^{56}Ni mass and *modelled* peak brightnesses between GRB-SNe and Ibc SNe (adopted for $h = 0.71$ cosmology from Richardson et al. 2006, Richardson 2009). Note: the Richardson model peak brightnesses can differ from the literature by ≈0.5 mag.

9.2.5 GRB 100316D/SN 2010bh

The fifth and latest known *bona fide* spectroscopic GRB-SN, GRB 100316D/ SN 2010bh, was also discovered by *Swift* (Starling et al. 2011). At a redshift of $z = 0.0591$, it had high-energy prompt properties that were remarkably similar to those of GRB 060218: it was also an XRF of unusually long duration (1300 s), it had a thermal component in addition to a synchrotron emission component with a low peak energy, a slow X-ray decay, and similar spectral hardness evolution.

The supernova features were typical of broad-lined SNe Ic and generally consistent with other spectroscopic GRB-SNe (Chornock et al. 2010). The Si II λ6355 expansion velocity was much higher than for SN 2006aj, more similar to SN 1998bw and SN 2003dh (Chornock et al. 2010, Patat et al. 2001, Hjorth et al. 2003). GRB 100316D/SN 2010bh was also distinct from GRB 060218/SN 2006aj in that their host galaxies were different, with the host of GRB 100316D more closely resembling that of GRB 980425 (Starling et al. 2011).

9.3 Supporting evidence for the GRB-SN connection

The highest redshift among the secure GRB-SNe is 0.1685 while the median redshift of *Swift* GRBs is above 2 (Jakobsson et al. 2006). Moreover, save GRB 030329, all of the spectroscopically secure events released significantly less energy than the median E_γ of known cosmological GRBs (Kaneko et al. 2007). It is, therefore, important to consider the evidence for GRB SNe at higher redshifts and for GRBs with $E_{\gamma,\mathrm{iso}}$ in the range 10^{50}–10^{54} erg (Frail et al. 2001). At higher redshift secure SN identification becomes difficult because the SN appears fainter, which leads to the difficulty of obtaining a sufficient signal-to-noise ratio in the broad SN features. The signal-to-noise problem is aggravated by the contamination of the host galaxy and the afterglow, which do not necessarily get comparatively fainter with redshift (see, e.g., Woosley & Bloom 2006).

There exists, however, substantial photometric evidence for late-time light-curve bumps. The first clear-cut case for a bump was GRB 980326 (Castro-Tirado & Gorosabel 1999, Bloom et al. 1999a), quickly followed by reanalysis of GRB 970228 (Reichart 1999, Galama et al. 2000) and GRB 990712 (Björnsson et al. 2001). Spectroscopic confirmation was attempted in several other systems with secure bumps, including GRB 011121 (Garnavich et al. 2003, Greiner et al. 2003b, Bloom et al. 2002b), XRF 020903 (Soderberg et al. 2005, Bersier et al. 2006), GRB 021211 (Della Valle et al. 2003), XRF 030723 (Fynbo et al. 2004, Tominaga et al. 2004), GRB 050525A (Della

Valle et al. 2006b), GRB 081007 (Della Valle et al. 2008), and GRB 101219B (Sparre et al. 2011), providing in all cases tentative evidence for SN spectroscopic features. Other systems with clear bumps include GRB 020405 (Price et al. 2003b), GRB 041006 (Stanek et al. 2005), GRB 080319B (Tanvir et al. 2010), GRB 090618 (Cano et al. 2010), and GRB 091127 (Cobb et al. 2010); GRB 020410 was suggested to have been discovered by its SN light (Levan et al. 2005a) and a bump of more dubious origin was detected in GRB 020305 (Gorosabel et al. 2005a). The bulk of the evidence points to Type Ic SNe and only in a few cases Type II SNe have been suggested (e.g., Garnavich et al. 2003, Gorosabel et al. 2005a). Only a few have IAU designations. In Table 9.1 we give a list of their properties. We also attempt to grade the GRB-SN connections according to the strength of the existing observational evidence. For an independent analysis of bursts up to 2003, see Zeh et al. (2004).

Generally, the picture supports the conclusion of the previous section, namely that SNe are ubiquitous in GRB light curves and that there is real diversity among such events (Zeh et al. 2004, Ferrero et al. 2006, Woosley & Bloom 2006, Richardson 2009). GRB-SNe are generally consistent with being broad-lined Type Ic, with a dispersion in both peak brightness, rise time, light curve width, and spectral broadness. They appear to represent the brighter end of the Ib/Ic population (see Fig. 9.4), but Woosley & Bloom (2006) showed that when the non-detections of GRB-SNe are accounted for, the two populations are statistically consistent with having been drawn from the same population. Clearly, as rare events, very bright Ic SNe are not routinely identified, nor are the fainter GRB-SNe. So as more uniform populations of GRB-SNe (and non-detections thereof) and Ib/Ic (and particularly Ic-BL) SNe are produced, it will be instructive to revisit this question of the comparative brightness and ^{56}Ni distribution.

At radio wavebands, GRB afterglows can be 10^4 times brighter at peak than typical Ib and Ic SNe (see Soderberg 2006): the reason is likely the difference between the coupling of energy to highly relativistic ($\Gamma \gtrsim 50$) ejecta (in the GRB/XRF case) versus sub-relativistic ($\beta\Gamma \lesssim 1$) ejecta (in the normal Ib/Ic case). The early radio brightness of SN 1998bw can be attributed to the large coupling of energy to trans-relativistic ejecta ($\beta\Gamma \approx$ a few; Kulkarni et al. 1998, Soderberg 2006).

Table 9.1. *Evidence for GRB-SNe.*

GRB/XRF	SN Designation	z	Evidence	Comments	Refs.
970228		0.695	C		1,2
980326			D	red bump	3,4
980425	1998bw	0.0085	A	spectroscopic SN	5
990712		0.433	C		6
991208		0.706	E	low significance	7
000911		1.058	E	low significance	8,9
011121	2001ke	0.362	B	spectral features	10,11,12
020305			E	not fitted by GRB-SNe	13
020405		0.691	C	red bump	14,15
020410			D	discovered via bump	16
020903		0.251	B	spectral features	17,18
021211	2002lt	1.006	B	spectral features	19
030329	2003dh	0.1685	A	spectroscopic SN	20,21,22
030723			D	red bump, X-ray excess	23,24
031203	2003lw	0.1055	A	spectroscopic SN	25
040924		0.859	C		26,27
041006		0.716	C		26,28
050416A		0.654	D	poor sampling	29
050525A	2005nc	0.606	B	spectral features	30
050824		0.828	E	low significance	31
060218	2006aj	0.0334	A	spectroscopic SN	32,33,34
060729		0.543	E	afterglow dominated	35,36
070419A		0.971	D	poor sampling	35,37,38
080319B		0.938	C	multiple color bump	35,39,40,41
081007	2008hw	0.530	B	spectral features	42,43,44
090618		0.54	C		36,45
091127	2009nz	0.490	C		46
100316D	2010bh	0.0591	A	spectroscopic SN	47,48
100418A		0.624	D		49
101219B		0.552	B	spectral features	50,51,52

The evidence according to the authors for a SN associated with a GRB is listed in column (4) according to the following scale: A: Strong spectroscopic evidence. B: A clear light curve bump as well as some spectroscopic evidence resembling a GRB-SN. C: A clear bump consistent with other GRB-SNe at the spectroscopic redshift of the GRB. D: A bump, but the inferred SN properties are not fully consistent with other GRB-SNe or the bump was not well sampled or there is no spectroscopic redshift of the GRB. E: A bump, either of low significance or inconsistent with other GRB-SNe.

References:

(1) Reichart (1999) (2) Galama et al. (2000) (3) Bloom et al. (1999a) (4) Castro-Tirado & Gorosabel (1999) (5) Fynbo et al. (2006) (6) Björnsson et al. (2001) (7) Castro-Tirado et al. (2001) (8) Lazzati et al. (2001) (9) Masetti et al. (2005) (10) Bloom et al. (2002b) (11) Garnavich et al. (2003) (12) Greiner et al. (2003b) (13) Gorosabel et al. (2005a) (14) Price et al. (2003b) (15) Masetti et al. (2003) (16) Levan et al. (2005a) (17) Soderberg et al. (2005) (18) Bersier et al. (2006) (19) Della Valle et al. (2003) (20) Stanek et al. (2003) (21) Hjorth et al. (2003) (22) Kawabata et al. (2003) (23) Fynbo et al. (2004) (24) Tominaga et al. (2004) (25) Malesani et al. (2004) (26) Soderberg et al. (2006a) (27) Wiersema et al. (2008) (28) Stanek et al. (2005) (29) Soderberg et al. (2007) (30) Della Valle et al. (2006b) (31) Sollerman et al. (2007) (32) Pian et al. (2006) (33) Modjaz et al. (2006) (34) Sollerman et al. (2006) (35) Fynbo et al. (2009) (36) Cano et al. (2010) (37) Cenko et al. (2007) (38) Hill et al. (2007) (39) Kann et al. (2008) (40) Bloom et al. (2009) (41) Tanvir et al. (2010) (42) Berger et al. (2008) (43) Della Valle et al. (2008) (44) Soderberg et al. (2008a) (45) Cenko et al. (2009) (46) Cobb et al. (2010) (47) Chornock et al. (2010) (48) Bufano et al. (2011) (49) A. De Ugarte-Postigo (private communication, 2010) (51) Olivares et al. (2011) (50) de Ugarte Postigo et al. (2011) (52) Sparre et al. (2011)

9.4 Supernova-less GRBs

Having presented the evidence that firmly established the GRB-SN connection we shall now present evidence for the existence of SN-less GRBs. These fall in two categories.

9.4.1 Short-duration GRBs

Short-duration, hard-spectrum GRBs (see Chapters 3 and 11) consistently do not exhibit SN features in their optical afterglow light curves. This was demonstrated already for the first two localized short GRBs, GRB 050509B (Bloom et al. 2006, Hjorth et al. 2005a) and GRB 050709 (Hjorth et al. 2005b, Fox et al. 2005) (Fig. 9.2).

Bright transient emission, dubbed a “mini SN” (Li & Paczyński 1998, Rosswog & Ramirez-Ruiz 2002), could be produced by radioactive elements that are synthesized during the rapid decompression of very dense and neutron rich material ejected during a NS-NS or a NS-BH merger (see, e.g., Rosswog et al. 1999). The emission is expected to peak around the optical-UV range within a day or so with a semi-thermal spectrum (Li & Paczyński 1998). Since modern models suggest a peak about 1000 times brighter than a nova, the term “kilonova” seems apt (Metzger et al. 2010).

For GRB 050509B, Hjorth et al. (2005a) used the model of Li & Paczyński (1998) and the upper limits shown in Fig. 9.2 to constrain the fraction f of the rest energy that goes into radioactive decay (assuming $z = 0.225$) (see also Kocevski et al. 2010). For a kinetic energy of order 10^{51} erg, the approximate upper limit was found to be $f = 10^{-5}$. The most efficient conversion of nuclear energy to the observable luminosity is provided by the elements with a decay timescale comparable to the time it takes the expanding ejecta to become optically thin. In reality, there is likely to be a large number of nuclides with a very broad range of decay timescales. Taking both into account, the Hjorth et al. (2005a) limit constrains the abundances and the lifetimes of the radioactive nuclides that form in the rapid decompression of nuclear-density matter – they should be either very short or very long so that radioactivity is inefficient in generating a large luminosity. In other words, unless the intrinsic energy in the outflow from GRB 050509B were $\ll 10^{51}$ erg, most of this energy was in sub-relativistic ejecta with a very small radioactive component during the optically thick expansion phase.

9.4.2 Long-duration GRBs

The absence of a SN signature in their light curves has been proposed as a defining characteristic of short GRBs. However, the discovery of another class of SN-less GRBs, namely long-duration GRBs like GRBs 060505 (Fynbo et al. 2006), 060614 (Fynbo et al. 2006, Della Valle et al. 2006a, Gal-Yam et al. 2006), and possibly 051109B (Perley et al. 2006) (and, in retrospect, XRF 040701; Soderberg et al. 2005, see below) with no SNe observed to deep limits, poses a challenge to an otherwise clean classification scheme. While there is a possibility of a chance coincidence of a GRB with a foreground galaxy (Cobb et al. 2006, Campisi & Li 2008), thereby giving the false impression of deep non-detections of SN light, the probability that all such associations are spurious becomes vanishingly small. One proposed resolution was to posit the $>$ 100 s long GRB 060614 as belonging to a "short" GRB population (Zhang et al. 2007). While we do not favor such a classification (Bloom et al. 2008), it highlights the importance of this new class of objects for our understanding of the GRB-SN connection.

GRB 060505 ($z = 0.089$) was a GRB with a duration of 4–5 s (depending on bandpass) and a non-zero spectral lag (namely, the delay of arrival of low energy photons with respect to higher energy photons) of 0.36 s, inconsistent with the lags of short GRBs (McBreen et al. 2008). It occurred in a star-forming region of a galaxy and exhibited all the characteristics of a normal long-duration GRB (Fynbo et al. 2006, Thöne et al. 2008, Xu et al. 2009)†. Still, no SN was detected down to a limit 100 times fainter than SN 1998bw (Fynbo et al. 2006, Fig. 9.2).

This opens up the possibility that some long GRBs either do not produce SNe at all, or produce very faint SNe, or that no radioactive material is formed or ejected. It is possible that these constitute fall-back SNe that produce a black hole without forming an accretion disk in which the Ni can form (Woosley 1993, Fryer et al. 2006, Moriya et al. 2010) or that the energy deposition is too low when the jet penetrates the star (Nomoto et al. 2006, Tominaga et al. 2007). Such events may finally represent the incarnation of the original "failed Ib" SN model (Woosley 1993).

The true fraction of such SN-less GRBs is unknown. It is noteworthy that several XRFs have been reported as showing no SNe (Soderberg et al. 2005, Levan et al. 2005b). Unfortunately, most of these have no measured redshift and were not sampled at the expected peak of the SNe, so the limits are

† GRB 060505 has been suggested to be a member of the short GRB class, belonging to the long tail of the duration distribution (Ofek et al. 2007). This is supported by the fact that it is an outlier of the so-called Amati relation (Amati et al. 2007) just like short GRBs. Note however that GRB 980425 is also a significant outlier, as is GRB 031203 if the *Integral* peak energy is adopted, c.f. Table 9.2.

strongly model dependent. The most promising candidate is XRF 040701, which occurred in a galaxy at $z = 0.21$ (Soderberg et al. 2005). *HST* observations around the time of the expected SN peak revealed no bump to 6 magnitudes fainter than the peak brightness of 1998bw. Soderberg et al. (2005) adopted the Predehl & Schmitt (1995) relation to infer an extinction of $A_V < 2.8$ mag from the constraints on the equivalent column density of neutral hydrogen $N_H < 5 \times 10^{21}$ cm^{-2} as measured from the soft X-ray emission in the *Chandra* spectrum. However, a study of 28 *Swift* bursts with joint observations of A_V and N_H (Schady et al. 2010) suggests an equivalent constraint of $A_V < 1$ mag, indicating that the limit on the absence of an SN related to XRF 040701 is indeed very strong, similar to those of GRB 060505 and GRB 060614. In this connection we note that the soft X-ray emission following some short GRBs could mimic an XRF if the initial short spike is too hard to be detected by *Swift*/BAT (Hjorth et al. 2005b).

9.5 Other properties of GRB SNe

Below we briefly address other important aspects of the GRB-SN connection. The basic properties of the GRBs, their SNe, and their host galaxies are summarized in Table 9.2.

9.5.1 Host galaxies

The host galaxies of GRB-SNe generally share the properties found for GRB hosts (see Chapter 13), namely they are sub-luminous, blue, young, and star-forming. In particular, the host galaxy of GRB 980425 (Fig. 9.1) has been the subject of fairly intense scrutiny because of its proximity (Fynbo et al. 2000, Foley et al. 2006, Hammer et al. 2006, Christensen et al. 2008, Michałowski et al. 2009). It has been suggested that the host galaxies of GRBs (Fynbo et al. 2003, Stanek et al. 2006, Fruchter et al. 2006) and GRB-SNe (Modjaz et al. 2008a) occur in low-metallicity environments. Fig. 9.5 shows the location of GRB-SN hosts in a line-ratio diagram (Christensen et al. 2008). As noted by Modjaz et al. (2008a), GRB-SNe occur in environments that are of systematically lower metallicity than broad-lined SN Ic with no known association to GRBs. The host galaxies of spectroscopic GRB-SNe discovered so far clearly have sub-Solar, but not very low, metallicities (Levesque 2011).

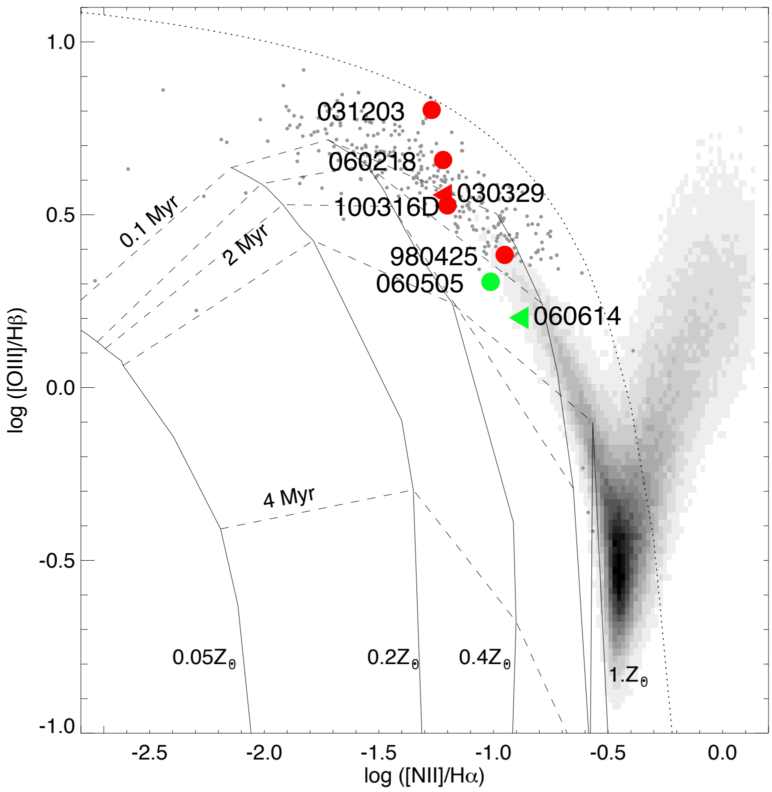

Fig. 9.5. Host galaxies of GRB-SNe have sub-Solar metallicities. The diagram (adapted from Christensen et al. 2008) shows the emission-line ratios [O III]/Hβ vs. [N II]/Hα for GRB-SN sites (full symbols) and SN-less GRBs (open symbols, cf. Fig. 9.2). The line ratios for GRB 100316D are for knot A in the host galaxy (Starling et al. 2011). Evolutionary models linking emission-line ratios at ages from 0.1 to 5 Myr for 0.05, 0.2, 0.4 and Solar metallicities ($Z_\odot = 0.016$, Asplund et al. 2005) are plotted as solid lines. The dotted curve denotes the separation of pure star-forming galaxies from AGN-dominated emission-line ratios. The greyscale area represents SDSS galaxies and the small grey dots represent SDSS galaxies with metallicities between 0.03 and 0.7 Solar. Two hosts with upper limits for [N II] are represented by triangles.

9.5.2 Timing

Iwamoto et al. (1998) found from modelling the light curve and spectra of SN 1998bw that the time of core collapse could be set to coincide with the detection of GRB 980425 to within $+0.7/-2$ days; a similar conclusion was reached by Kulkarni et al. (1998). Hjorth et al. (2003) attempted to date SN 2003dh spectroscopically, under the assumption of its parallel spectral evolution with SN 1998bw and concluded that SN 2003dh began ± 2 days relative to GRB 030329 (to this should be added the above uncertainty of $+0.7/-2$ days of the SN 1998bw dating). Finally, the near-simultaneous detection of GRB 060218 and what was interpreted as the shock breakout of SN 2006aj firmly linked the times of explosions of this GRB and its associated SN (Campana et al. 2006). Supranova models have simply not withstood the test of observations with new events.

9.5.3 Asymmetry and asphericity

Asphericity may be a common feature of core-collapse SNe (e.g., Leonard et al. 2006, Maeda et al. 2008) and hence GRB-SNe. There is some observational evidence that GRB-SNe may be aspherical from the shapes and relative expansion velocities of emission lines, including highly peaked oxygen lines in nebular spectra (e.g., Mazzali et al. 2001, Maeda et al. 2006, Mazzali et al. 2007a,b). Similarly, imaging polarimetry and spectropolarimetry point to aspherical emission (e.g., Greiner et al. 2003a, Gorosabel et al. 2006, Maund et al. 2007), but the exact interpretation of these results and their implications for the shape and internal composition of GRB-SNe is still under debate (e.g., Modjaz et al. 2008b, Maund et al. 2007, Maeda et al. 2008).

9.5.4 Circumburst environment

A massive-star progenitor should expel mass pre-explosion and a signature of a "wind-stratified" medium should, in principle, be manifest in the observations of the afterglow. Despite this nominal expectation, few GRB afterglows are significantly better fit by a medium consistent with a constant mass loss (circumburst mass density $\rho \propto r^{-2}$, with r as the distance to the center of the explosion; Chevalier & Li 1999, Panaitescu & Kumar 2002) than a constant-density medium. There are some reasonably strong cases for a $\rho \propto r^{-2}$ circumburst medium (Price et al. 2002) but, in general, the nature of the density profile proxied by the afterglow is both model-dependent and highly coupled to measurements of other afterglow-specific parameters

(e.g., Yost et al. 2003, Starling et al. 2008). Given the preponderance of direct evidence linking GRBs and massive star deaths, we feel that the lack of a tell-tale wind signature must imply an incomplete understanding of afterglow emission mechanisms and/or the details of the progenitor evolution rather than serve as disconfirming evidence for the connection. Indeed, this lack has been accommodated in models as due to the homogenizing influence of the wind reverse shock of the density surrounding the star (Wijers 2001, Ramirez-Ruiz et al. 2005) and varying mass-loss histories of the progenitor (van Marle et al. 2006).

GRB 021004 showed absorption systems at high-velocities relative to the host galaxy in the afterglow, suggestive of a Wolf-Rayet wind (Mirabal et al. 2003, Schaefer et al. 2003, Castro-Tirado et al. 2010); note, however, that it has been argued by Chen et al. (2007) that the absorption systems are unlikely to have arisen from within the circumburst environment. In general, the absence of high-velocity signatures in absorption spectra of several other events have been explained as due to the photo-destructive power of the early afterglow (Prochaska et al. 2006, Chen et al. 2007). Interestingly, an initial study of high-ionization species (of, e.g., nitrogen), expected to survive the early afterglow, appear to favor low-velocity circumburst outflow pre-explosion (Prochaska et al. 2008).

Finally, in a study of the high signal-to-noise *Swift* X-ray spectrum of GRB 060218, Campana et al. (2008) inferred CNO abundances much larger than the Solar value, presumably due to enriched circumburst material. Interpreting the relative abundance ratios of CNO in the context of the models of Yoon et al. (2006) indicates that the required mixing limits massive progenitor star models to have sub-Solar metallicity and rapid rotation.

9.6 Outlook after a decade of the GRB-SN connection

It now appears unassailably established that many (if not most) long-duration GRBs are connected with the death of massive stars: the same event that produces a GRB also produces a substantial mass in ^{56}Ni and a large coupling of kinetic energy ($> 10^{51}$ erg) to non-relativistic ejecta. The pre-explosion jettisoning of hydrogen and helium appears to be an observational requirement of the progenitor (see Chapter 10 for a theoretical review). Still, we do not understand what sets a stripped-envelope GRB/SN progenitor apart from other SN progenitors which do not produce GRBs.

From demographic studies of the relative rates of GRBs and SNe (e.g., Bloom et al. 1998, Berger et al. 2003a, Podsiadlowski et al. 2004, Soderberg et al. 2004, Soderberg 2006) it is clear that only a tiny fraction ($\sim$1%) of

Table 9.2. *Properties of the Associated GRBs and SNe.*

GRB	**980405**	**030329**	**031203**	**060218**	**100316D**
SN designation	1998bw	2003dh	2003lw	2006aj	2010bh
z	0.0085	0.1685	0.1055	0.0334	0.0591
High-Energy and Afterglow Properties					
T_{90} (s)	34.9 ± 3.8	22.9	37.0 ± 1.3	2100 ± 100	1300
S_X/S_γ	0.58	0.56	0.49(4±2)	3.5	1.56
$E_{\rm peak}$ (keV)	122 ± 17	70 ± 2	$> 71(< 20)$	4.7 ± 1.2	18^{+3}_{-2}
$E_{\gamma,\rm iso}$ (10^{51} erg)	9×10^{-4}	13	0.17	0.04	0.06
E_γ (10^{51} erg)	$< 9 \times 10^{-4}$	0.07–0.46	< 0.17	< 0.04	0.0037–0.06
Supernova Properties					
$M_{\rm bol,peak}$ (mag)	−18.6	−18.7	−18.9	−18.2	−17.5
$v_{\rm exp}$ at 10 d (10^3 km s^{-1})	24	29	21	19	
M(^{56}Ni) (M$_\odot$)	0.38–0.48	0.25–0.45	0.45–0.65	0.20–0.25	~ 0.10
M$_{\rm ejecta}$ (M$_\odot$)	10±1	8±2	13±2	2±0.5	~ 3
M$_{\rm ZAMS}$ (M$_\odot$)	35–45	25–40	40–50	20–25	
$E_{\rm SN}$ (10^{51} erg)	50±5	40±10	60±10	2±0.5	~ 10
Host Galaxy Properties					
$M_{\rm B,host}$ (mag)	−17.7	−16.5	−21.0	−15.9	−18.8
Hα SFR (M$_\odot$ yr^{-1})	0.23	0.6	12.3	0.065	> 0.17
M$_*$ (10^9 M$_\odot$)	1.1	1.5	~1	0.05	
SSFR (Gyr^{-1})	0.21	0.4	1	1.3	
Metallicity	8.25–8.39	7.8	8.12	8.0	8.23

High-energy and afterglow properties: taken from Kaneko et al. (2007) and references therein, supplemented by Watson et al. (2004, 2006), Starling et al. (2011), and Woosley & Bloom (2006) and references therein. The values in parentheses for S_X/S_γ and $E_{\rm peak}$ given for 031203 are inferred by Watson et al. (2004) using the X-ray dust echo. Supernova properties: taken from Mazzali et al. (2007b) and references therein. Host galaxy properties: absolute magnitudes from Sollerman et al. (2005), Wiersema et al. (2007), and Sollerman et al. (2006), stellar masses from Castro Cerón et al. (2010), and star-formation rates from Christensen et al. (2008), Gorosabel et al. (2005b), Prochaska et al. (2004), and Margutti et al. (2007). Metallicities here are 12 + log(O/H), as compiled in Margutti et al. (2007). Values for GRB 100316D are from Starling et al. (2011) and Bufano et al. (2011); the metallicity in this case refers to knot "A" close to the SN site. Key: "T_{90}": Duration of 90% of the event in γ rays. "S_X/S_γ": Ratio of fluence in 2–30 keV band to fluence in 30–400 keV band. A ratio larger than 1 indicates an XRF. "$E_{\rm peak}$": Photon energy where νf_ν peaks. "$E_{\gamma,\rm iso}$": Isotropic equivalent energy output in γ rays (i.e., not corrected for beaming). "E_γ": Energy output in γ rays (i.e., corrected for beaming). An upper limit indicates that no beaming was measured. "$v_{\rm exp}$": Photospheric expansion velocity. "M(^{56}Ni)": Mass of ^{56}Ni synthesized. "M$_{\rm ejecta}$": Mass of the ejecta. "M$_{\rm ZAMS}$": Mass of the progenitor star (on the zero-age main sequence). "$E_{\rm SN}$": Energy associated with the outflow of the SN. "SFR": Star-formation rate. "M$_*$": Stellar mass. "SSFR": Specific star formation rate (SFR/M$_*$).

core-collapse events that produce Ibc SNe also produce a detectable GRB. Even Ic-BL SNe, which themselves comprise a small fraction of the core-collapse SN rate (Guetta & Della Valle 2007), are seldom associated with a GRB. Since GRB jets are thought to be highly collimated (and relativistically Doppler beamed), whereas SNe are roughly isotropic, the difference in rates might simply be due to geometry and viewing-angle effects. Soderberg et al. (2006b) found no evidence for highly energetic and off-axis components in radio observations of Ic-BL SNe, statistically disfavoring the notion that all Ic-BL SNe also harbor GRB-like ("central engine driven") features. The recent inferences of mildly relativistic ejecta in the Type Ic SN 2009bb (Soderberg et al. 2010) may suggest a central-engine driven origin. At minimum, it seems such objects support the notion of a continuum of energy and mass coupled to relativistic speeds across SNe.

History is some guide here: though the GRB associated with SN 1998bw appeared to belong to a distinct subclass in terms of energetics, more recent events point to a continuum of energy coupled to the relativistic ejecta. Likewise, though it now appears that GRB 060614 and GRB 060505 represent a distinct subclass in terms of ^{56}Ni production ($M_{V,\mathrm{peak}} > -13$ mag), transition GRB-SNe with faint SNe ($M_{V,\mathrm{peak}} \sim -16$ mag, c.f. Fig. 9.2) may be found, pointing to a continuum of explosive nucleosynthesis. Indeed, there is evidence for very faint ($M_{V,\mathrm{peak}} \sim -14$) extragalactic events residing on the tail end of the ^{56}Ni production distribution in core-collapsed Type II SNe (Pastorello et al. 2007, Fig. 1), although the existence of ultra-faint Type Ibc SNe is currently debated (Valenti et al. 2009, Foley et al. 2009, Moriya et al. 2010). This supports the physical intuition that massive stars which explode can produce a wide range of ^{56}Ni mass with a broad range of explosion energies (c.f., Mazzali et al. 2007a).

The distribution of available energy into various channels (neutrinos, gravitational waves, γ rays, particles, kinetic motion of the relativistic outflow, kinetic motion of the non-relativistic SN outflow) is far from understood. There is reasonable evidence, from the metrics proxying the bulk kinetic energy of the afterglow (E_K) and the measures of energy promptly released in γ rays (E_γ), to suggest an overall envelope in the energy budget of the explosions (Berger et al. 2003b). More recent work including very luminous *Fermi* GRBs (Cenko et al. 2010), however, suggests that E_γ and E_K are correlated and so the total budget may not be similar among all long-duration events.

In all cases where the energy associated with the non-relativistic outflow of the SN (E_{SN}) has been modelled, it appears to be larger than E_γ and E_K. To gain some insight into the energy partitioning, it is tempting to

try to connect the amount of SN energy (and the other basic parameters $M_{\rm ejecta}$ and ^{56}Ni mass) with the other measured energies associated with the GRB and afterglow. The danger is that observational biases that could induce apparent correlations are severe. For example, lower E_γ events are more readily detected at low redshift, improving the SN detection possibility. Likewise, lower E_K manifests itself as fainter afterglow, also improving SN detection odds. Indeed, a careful statistical study of the relationship between GRB-SN peak brightnesses and GRB energetics found no strong correlation (Koen 2009). Still, this accounting for the global energy budget should continue to be pursued, especially in the next decade as gravitational-wave and neutrino detectors begin to yield insight into the energy budgets of generic core-collapsed SNe in the local Universe.

The current spectroscopic evidence for GRB-SNe is not of high enough quality and the number of sample members is insufficient to address the issue of whether there are systematic differences between low-redshift (low E_γ) SNe and higher-redshift (high E_γ) SNe (Soderberg et al. 2005, Sollerman et al. 2000). Clearly, the group of 5 low-redshift GRBs ($z < 0.1685$) with spectroscopically secure SN identifications appear subenergetic in terms of beaming-corrected E_γ than the majority of the higher redshift events. Establishing the GRB-SN connection for higher-redshift, more energetic GRBs will bean observational challenge, requiring 30–40-m class telescopes. Other aspects of such an endeavor will be to determine the fraction of SN-less GRBs and their relation to the GRB properties and progenitors, as well as possibly finding the intermediate ^{56}Ni production GRB-SN (which we might call "gap" GRB-SNe) discussed above (if indeed they exist). If some unidentified TeV sources in the Galaxy are associated with GRB remnants (Ioka & Mészáros 2010), then detailed chemical studies of the explosion byproducts may provide new insight into the progenitors (akin to late time studies of SN remnants; Badenes et al. 2009).

A hint that surprises may be in store are the very significant light curve bumps in some GRB afterglows that do not fit our current understanding of the GRB-SN connection:

- GRB 020305 showed a clear bump, both in the light curve and in the spectral shape (Gorosabel et al. 2005a). Each of these were found to be consistent with (different) SN templates, but no single SN template could fit both features simultaneously.
- XRF 030723 had a very significant and well-sampled bump showing a clear reddening at the peak of the bump (Fynbo et al. 2004) and was well fitted by a SN model (Tominaga et al. 2004). However, a reported

possible simultaneous X-ray increase (Butler et al. 2005) shed doubts on the SN origin of the light curve bump.

What are these bumps? Are they indications of SNe with different properties from those discussed so far or do they point to mechanisms for producing SN-like bumps but of an entirely different origin (e.g., dust echoes, Esin & Blandford 2000)? We note that in all cases, more limited observational information (e.g., only one band, no X rays) ironically could have led to a higher confidence grade in Table 9.1. And it highlights the importance of spectroscopic confirmation of SNe, as emphasized in this chapter.

As unconventional SNe may be related to normal GRBs, unconventional high-energy events may be related to normal SNe. The discovery of the Type Ib SN 2008D related to an X-ray transient (i.e., not a GRB) (Soderberg et al. 2008b, Mazzali et al. 2008, Malesani et al. 2009, Modjaz et al. 2009) suggests that SNe may reflect a range of high-energy properties, not only GRBs. It opens up the possibility that all SNe may be related to detectable high-energy events and that GRBs may be only one possible manifestation of these, perhaps as part of a range of high-energy properties (Xu et al. 2008, Li 2008).

The discovery of SN-less GRBs suggests that massive stars may die without sending high-energy electromagnetic signatures of their deaths, e.g., off-axis events, and with no bright SN event. The fraction of such events is unknown. Even in the most optimistic cases (Fryer et al. 2002, Ott et al. 2006), gravitational-wave and neutrino signatures would only be detectable for the very nearest (and, hence, uncommon) events. However, there may be a case for mapping and subsequently revisiting/monitoring all the massive stars in the nearby Universe with *HST*, *JWST*, or *Euclid*. This would give an independent handle on the fraction of disappearing stars (Kochanek et al. 2008), at least in the types of galaxies surveyed. In a complementary approach, the search for kilonovae or similar new types of radioactive-powered events would be important to map all the possible cosmic explosions, including those resulting from (short) GRBs.

The connection between some GRBs and massive stellar deaths holds great importance in the utility of GRBs as probes of the distant Universe. First, massive stars trace the location of stellar nurseries at high redshift. Though the first few seconds of afterglow light are generally thought capable of destroying most spectroscopic signatures of the circumburst and molecular cloud environments, spectroscopy of afterglow in some rare cases should inform the nature of these close-in environments (Prochaska et al. 2008, 2009). Second, the connection, especially emerging in low-metallicity hosts,

implies that GRBs are tracers of instantaneous star formation (e.g., Butler et al. 2010). Not only can high-resolution spectroscopy directly constrain individual star-formation histories of hosts (Calura et al. 2009), the comparative demographics of detections at various wavebands (particularly, γ rays, X rays and optical/IR) should supply direct constraints on the fraction of obscured star formation in the Universe (e.g., Djorgovski et al. 2003). This is one of the great hopes for the importance of the so-called "dark bursts" (Perley et al. 2009; see Chapter 6). Last, and perhaps most compelling, is that since GRBs appear to arise from low-metallicity, high-mass stars, they should exist beyond the redshifts of furthest known objects today; indeed this notion stands on rather firm observational ground now with the identification of several events above redshift $z = 6$. GRBs, then, are likely the most recognizable events in the very early Universe, detectable by the next-generation of satellites and signposts (for *JWST* and the next generation 30-m telescopes) to the first galaxies. Even moderate-resolution spectroscopy of GRB afterglows beyond $z = 7$ (e.g. with GRB 090423 at $z = 8.2$; Tanvir et al. 2009) would be unique *in situ* tracers of the cosmo-chemical evolution of the infant Universe (e.g., McQuinn et al. 2009).

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